Comparative analysis of PIP-II to the designs used in different facilities worldwide.

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PIP-II Technical Workshop

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A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST

Fundamental coupler for superconductive cavities is rather complicated device. It is described by many parameters (features). This a list of some of them:

- Input – output: Waveguide, waveguide-coaxial, coaxial.
- Number of windows: one window, two window.
- Window(s) shape: cylindrical, planar.
- Adjustability: fixed, adjustable.
- Outer conductor cooling: straps, double wall
- Copper coating: coated, not coated.
- Ceramic coatings: TiN, TiOx, not coated.
- Multipactor suppression: HV bias, no HV bias.
- Cooling media: water, air, no cooling.
- Window material: aluminum oxide, beryllium oxide.

Number of possible combinations: > 3 x 2 x 2 x 2 x 2 x 2 x 3 x 2 x 3 x 2 = **3456**

We will consider some of them.

One window vs two window.

Most discussible question: how many windows SRF coupler should have.
Mostly SRF couplers has a single window.
Two windows couplers are TTF-III like couplers(TTF-III, Cornel ERL) KEK ILC, Argonne.
Typically, two window couplers air moldered power level couplers.

Pros and Cons.

Two windows, Pros:
- More save for accelerator: one broken window does not cause serious consequences;
- Cold part is short, eraser to install string into cryomodule.

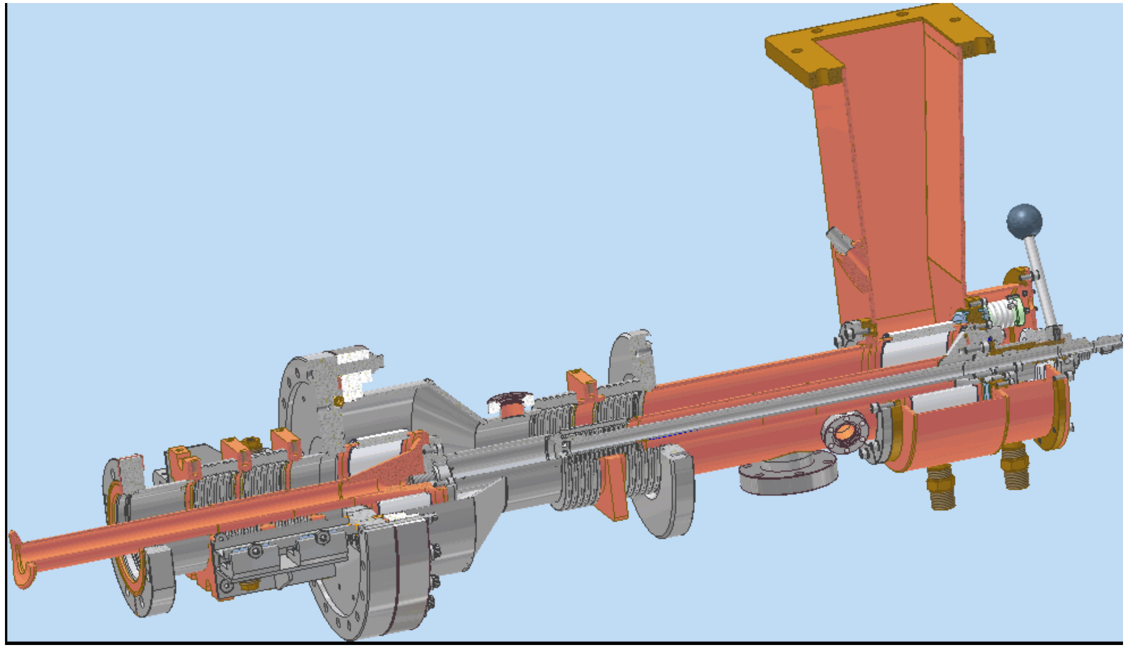
Two window, Cons:
- More complicated configuration, more expansive.
- Difficult (impossible) to detect a break/leak of cold window(it is leak from isolating vacuum to cavity vacuum).
- Difficult to provide effective cooling of cold part of antenna.
- Less effective (cold part of antenna is cooled through cold “80K” window.)

Single window, Pros:
- Simpler configuration, less expansive.
- Easy to cool antenna. It is important for high power couplers.

Single window, Cons:
- Broken window can cause serious consequences. Big power safety margin is required.
- Distance from cavity flange to window is longer, it is not so convenient to install string to cryomodule.

Example of powerful coupler with two window.

HIGH POWER INPUT COUPLER FOR CORNELL ERL INJECTOR CAVITIES



Parameters of Couplers
Central frequency 1300 MHz
Bandwidth ±10 MHz
Maximum RF power transferred to matched load 65 kW
Number of ceramic windows 2
*Q*ext range 9.2×104 to 8.2×105
Cold coaxial line impedance 60
Warm coaxial line impedance 46
Coaxial line OD 62 mm
Antenna stroke 16 mm
Heat leak to 2 K < 0.2 W (360W)
Heat leak to 5 K <3 W (750W)
Heat leak to 80 K < 75 W (1500 W)

It is impressive powerful 65 kW coupler.
Cryo-plant works mostly (1500W) to cool down the antenna (my guess).

When PIP-II couplers were started to design the operating power level was ≥ 100 kW with high level of reflection.
Single window configuration was chosen.

Fixed or adjustable?

Adjustable, Pros.:

- Allows to match cavity with “any” current perfectly, save power of RF source not overheat couplers.
- Allow to changer coupling of each cavity separately. It is important if several cavity are powered from oner source.

Adjustable, Cons.:

- More complicated, more expansive.
- It requires movable parts and bellow(s) at vacuum part. It makes coupler less reliable during operation and transportation.
- It is not easy to make reliable copper coatings of bellows.
- It is not easy to cool bellows in vacuum.

Fixed, Pros.:

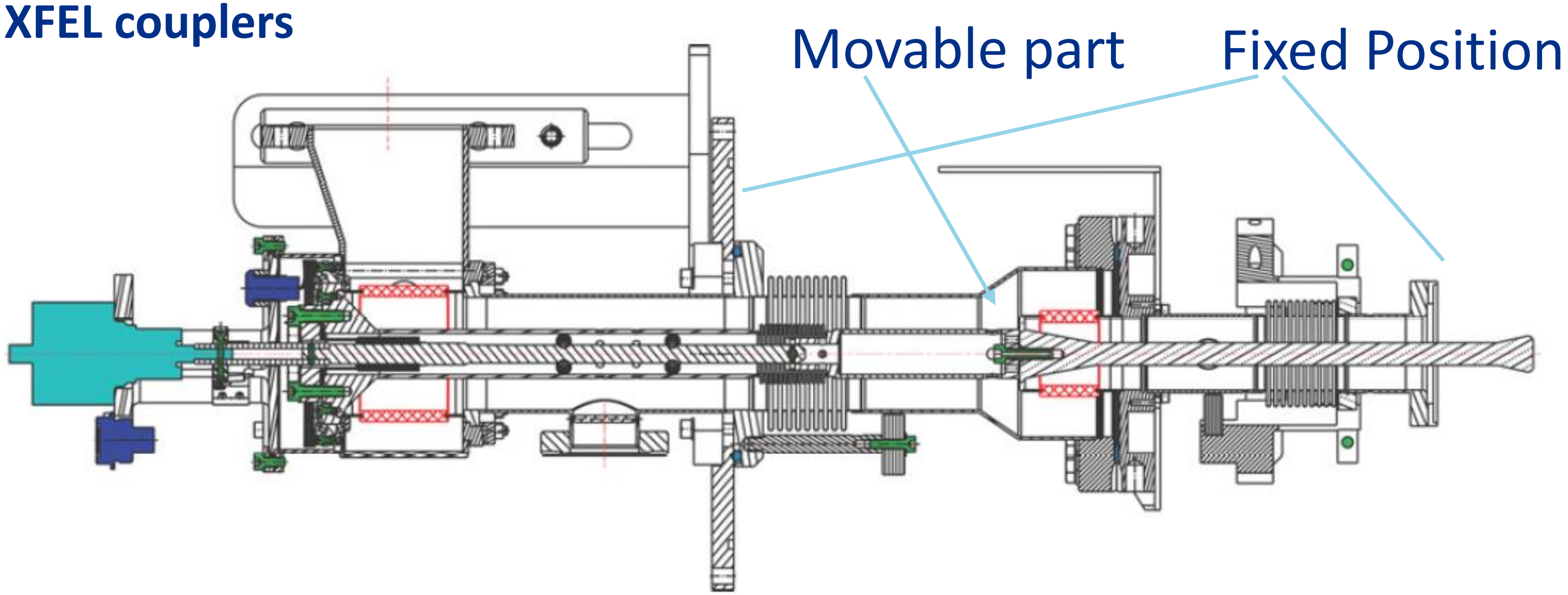
- Simpler configuration, less expansive.
- No movable parts, no bellows in vacuum, more relabel.
- Procedure of copper coating (if any) simpler and more reliable.

Fixed, Cons.:

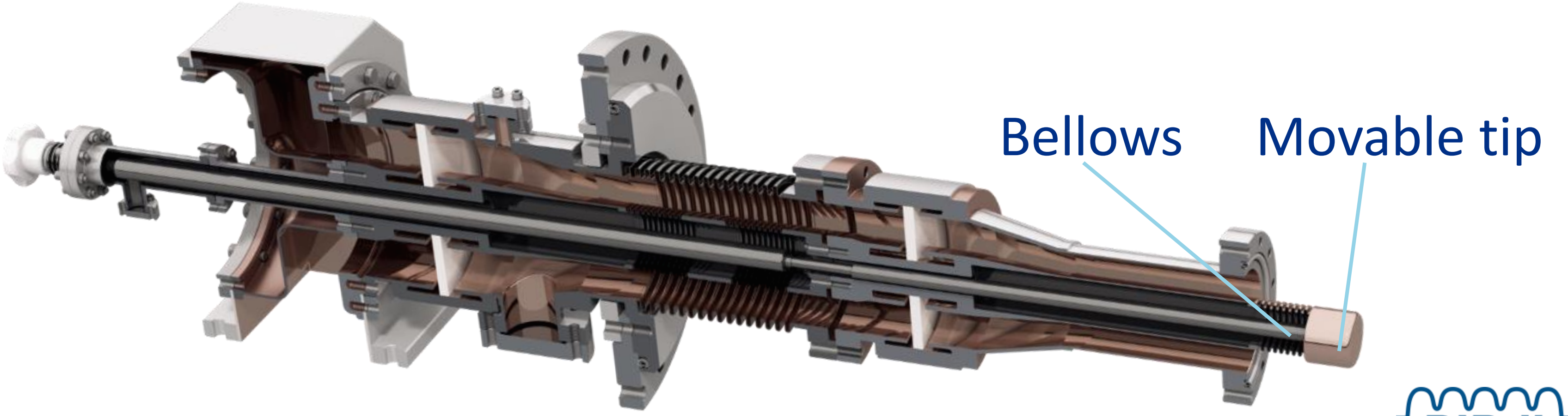
- Mismatched if operating current change. It requires additional power from RF source, more power dissipated in coupler.
- More difficult to apply in configuration with one power source for several cavities.

Two examples of adjustable couplers

XFEL couplers



KEK STF coupler



- Each cavity of PIP-II has its own RF source, the is no problem to adjust coupling of cavities powered from common RF source to control amplitude and pulse shape. It can be done by controlling RF source.
- Deviation of beam current from optimal causes reflection power from cavity. It requires additional power from RF sources and power dissipation in couplers becomes higher. But this effects are not too sensitive to current change: two times current change results only 10% power increasing comparatively with optimal value.

Configurations with fixed coupling was chosen for PIP-II couplers.

Cooper coating.

Copper coating is used to reduce Ohmic losses in coupler, reduce a heating of coupler and improve its cryogenic properties. **All (almost all) couplers in world use a copper coating**.

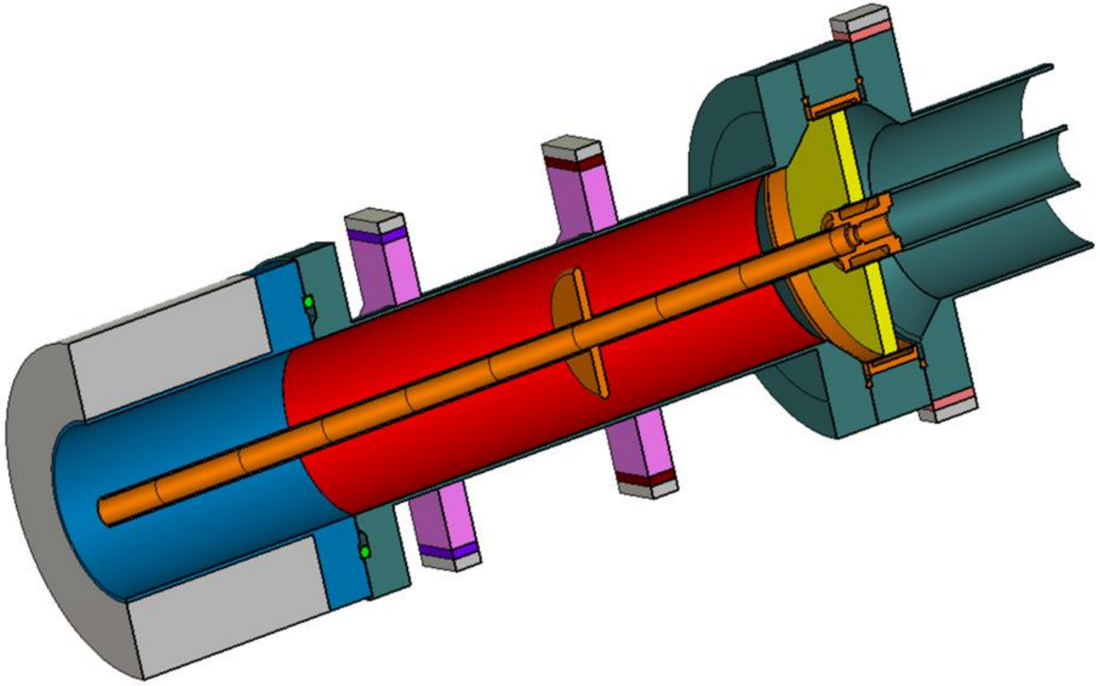
Problem with copper coatings:
Copper coatings procedure is rather “sensitive” operation and failures is rather possible.
Copper flaking possible during operation. It will kill a performance of superconductive cavities.
Copper coating increases a thermal conductivity of outer conductor. It increases a static cryogenic loading of coupler.

It is better to avoid copper coating if it possible and we tried to do it. Prototypes of SSR1 couplers were made without copper coatings. Several reasons allowed us to do it: not so high power ~ 5 kW, relatively large diameter of outer conductor 73mm, high impedance 105 Ohm. All this allowed to keep cryogenic loadings acceptable

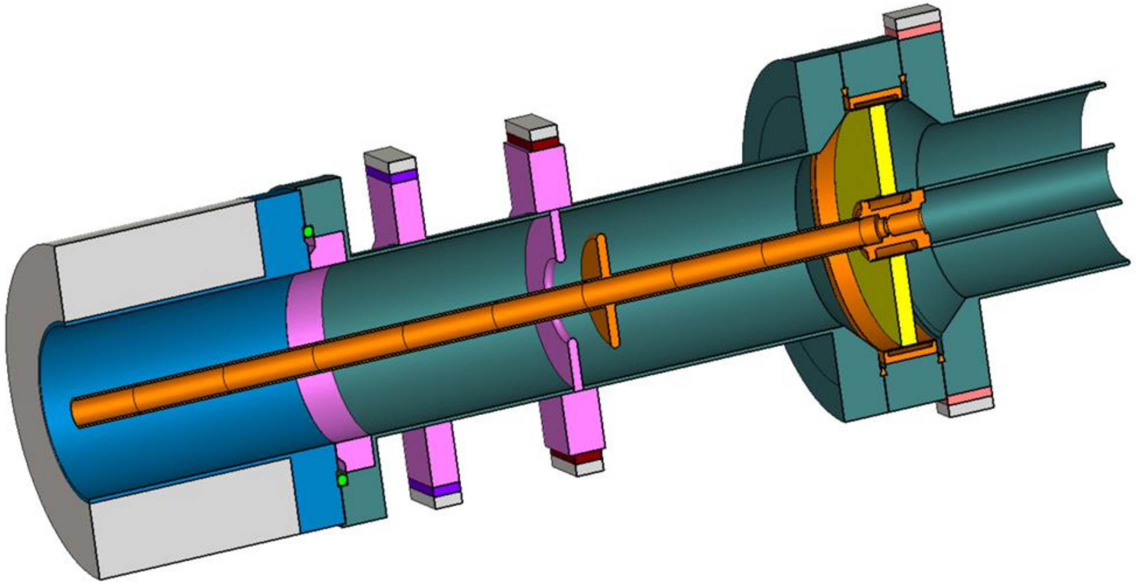
SSR2 coupler (or universal SSR coupler) should operate at higher power ~ 11 kW with some reflection and SSR1 coupler configuration does not work.

But and for SSR2 coupler we found solution without copper coating:

SRR2 coupler with copper coating, current design:



“SSR2” coupler without copper coating:



Static loading (with T-radiation)

	2K	5K	50K	293K
Cu, 0.8mm	0.73	1.55	13.4	-5.2
Cu, 1.65mm	0.79	2.2	12.3	-9.1
no Cu, 0.8mm	0.08	0.67	8.4	-3.7
no Cu, 1.65mm	0.1	1.36	7.7	-3.7

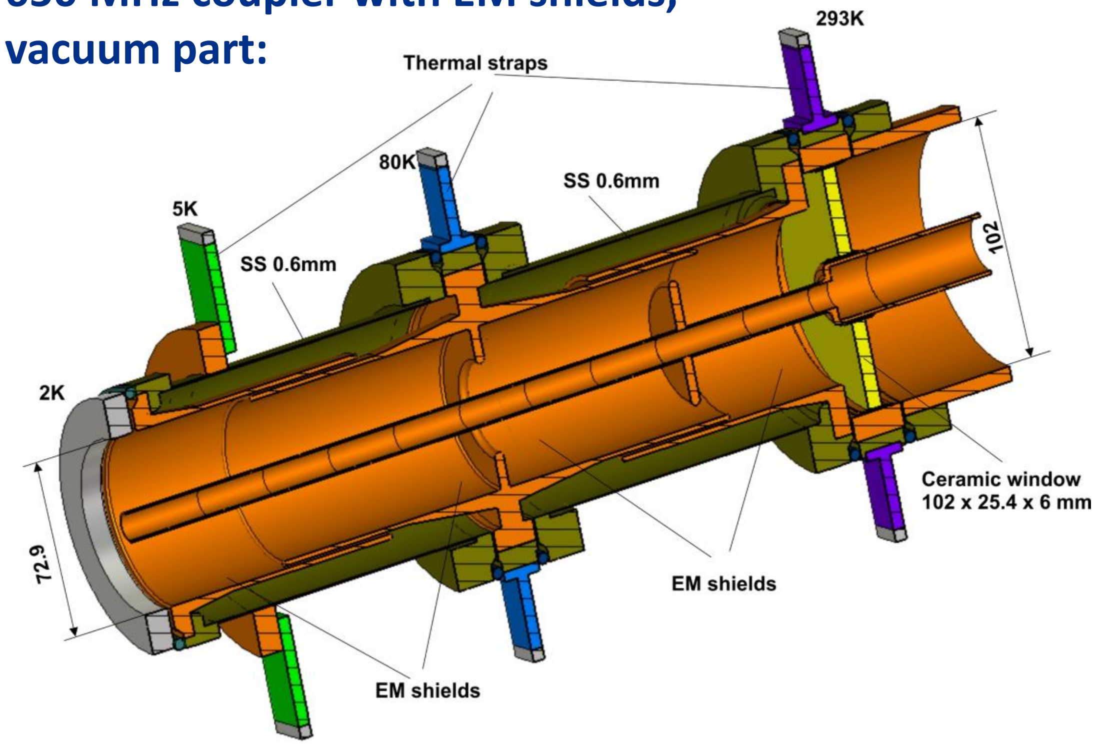
Total loading (with T-rad.) for 11kW, 20% reflection

	2K	5K	50K	293K
Cu, 0.8mm	**0.83**	1.79	14.2	-4.7
Cu, 1.65mm	**0.90**	2.54	13.5	-4.7
No Cu, 0.8mm	**0.50**	1.83	9.8	-1.8
No CU, 1.65mm	**0.51**	2.55	9.1	-1.8

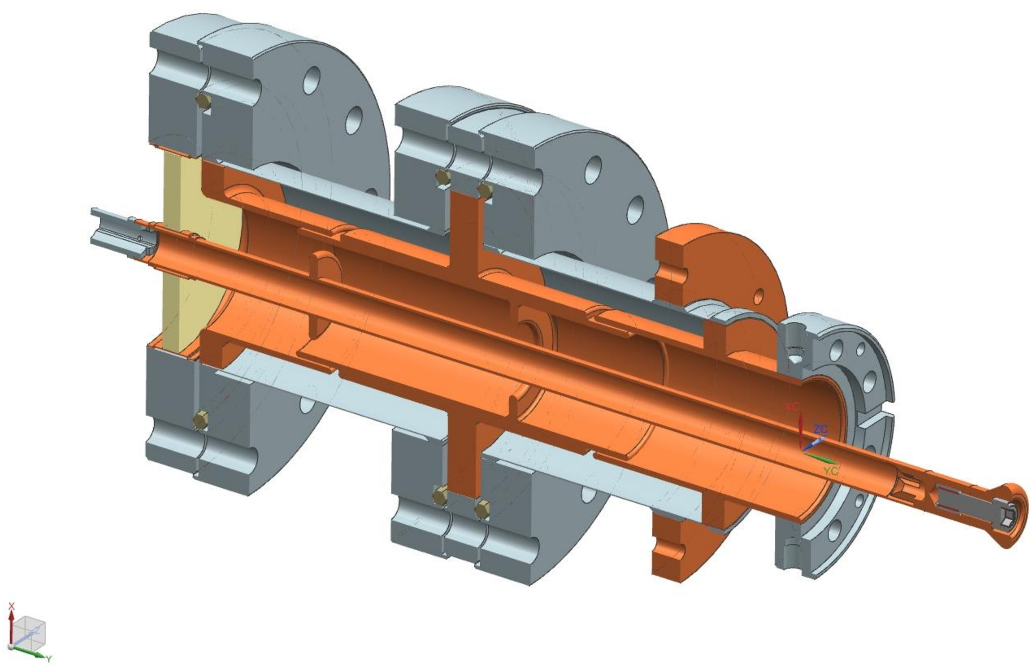
Configuration without copper coatings has even better cryogenic properties for 11 kW, CW.
In case of **Cu-coating**, it is mostly **static** loadings. In cease of **"no Cu"** it is mostly **"dynamic"** loadings.
It means if power will be increased (twice, for example) the cryogenic lodgings of "Cu" will not change much, but loadings of "no Cu" will increase proportionally to power. By this, **"no Cu" has less potential for power upgrade.**
Because of this and because of "Cu" requires less brazed parts, our coupler team preferred "Cu" configuration.

Configurations without copper coatings for 650 MHz and 1300 MHz couplers exist as well.
They were built and successfully tested at room temperature test stands.

650 MHz coupler with EM shields, vacuum part:



1300 MHz coupler with EM shields, vacuum part:



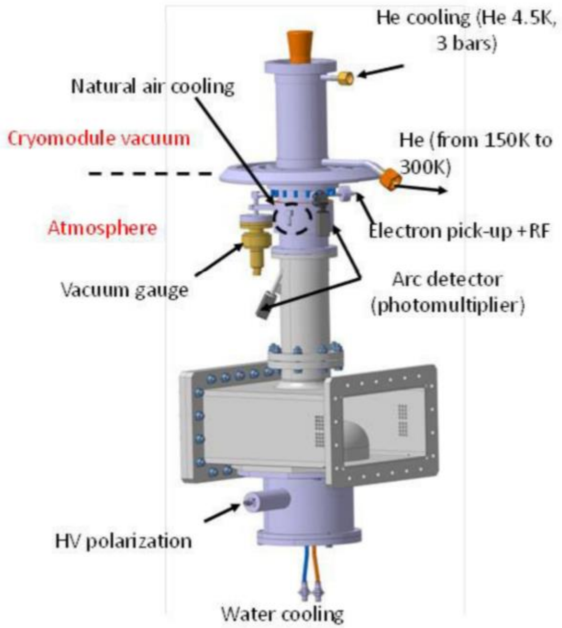
Tested up to 50 KW, CW, full reflection.

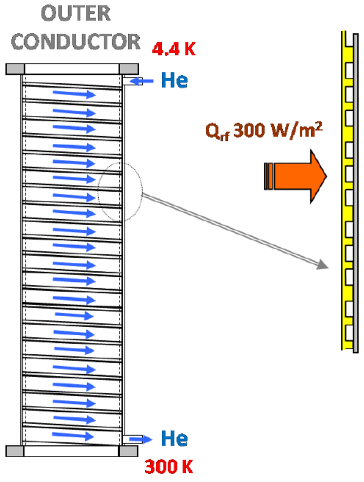
Tested up to 27 kW, CW, TW.

Configurations with EM shields will be indispensable for accelerators with minimal cryogenic loads.

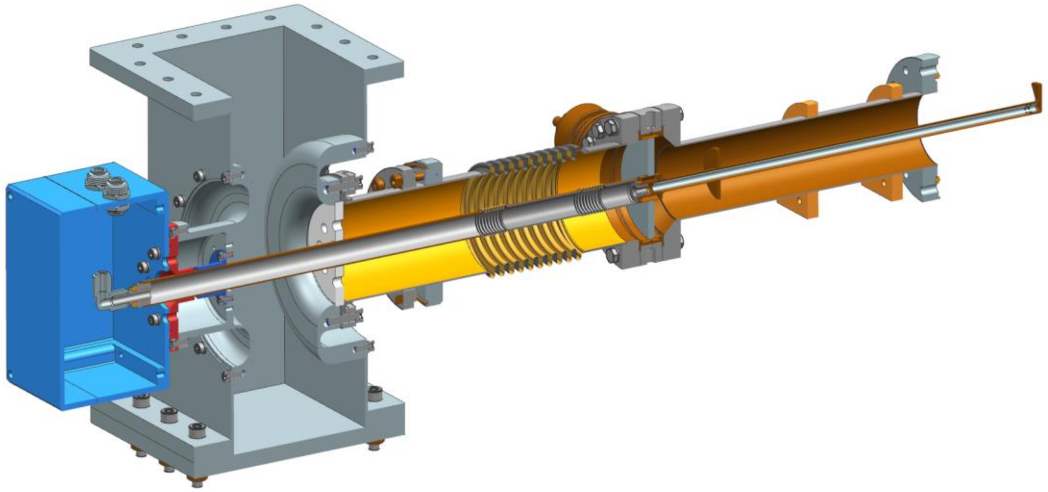
Double wall vs single wall with thermal intercepts.

Example of coupler with double wall outer conductor, IFMIF coupler:





Example of couple single wall outer conductor, PIP-II 650 MHz coupler:



Pros: No needs straps – no depends on thermal contacts, effective cooling.
Cons: Complicated structure, additional vacuum weld and joints. Less effective – thicker wall.

Pros: Simple structure, less vacuum welds and joints. More effective - thinner walls.
Cons: Requires thermal straps and good thermal contacts.

Single wall configuration was chosen for PIP-II couplers.

PIP-II

TiN coatings of ceramics.

Typically surfaces of ceramic windows are coated with TiN (TiO_2 – CERN) to reduce secondary electrons emission yield. **We proved experimentally by room temperature and cold tests that couplers can work successfully without TiN coatings.**
Nevertheless we are still considering a possibility to coat ceramics with TiN.
To investigate properties of coating we coated (CPI) five D = 73mm ceramics disks with different thickness of TiN:

Disk #	1	2	3	4	5	6
Thickness (nm)	8	12	17	22	32	0

First, we did find any additional losses in ceramics with 32nm thickness of TiN coatings.
Sincerity of loss tng. measurements ~ 1E-5. Measured loss. tng was ~**1.4E-5** at F ~ 2.7GHz.

Second, we could not measure surface resistance of ceramics with 32 nm coating. Measurements was done with voltage 25V, estimated resistance R > 250 GOhm.

Information from different labs:

Company	Resistance	RF losses
CPI/FNAL	> 250 GOhm	32nm, no losses
KEK	>1E+15 Ohm	?
DESY	10-40 GOhm	?
Euclid	10kOhm – 1Mohm	?
SLAC	20n - measurable	5n – big losses
France	5nm, 120 micOhm*cm	?

“dielectric”

“metal”

The “same” substance, but properties are very different.

There are several important question we have to answer:

- **What is the right thickness of coating?** SLAC does 2nm thickness, 5nm – losses are significant.

We asking for 10nm and cannot notice the losses for 32nm.

- **How to check the thickness?**
- **What does it happen with TiN film in vacuum under electron bombardment?**
- **Can nonconductive film become conductive?**

We have negative experience with RFQ coupler window. Coated ceramics become conductive during operation. It was impossible to apply bias. We don't know exactly what happened. Noncoated windows (but different configuration) work well.

We do not understand well what is TiN and how it works.
May be it is more save not to coat ceramics if coupler can work without coating?

We will continue to investigate TiN, but couplers will be produced without TiN. Ceramics will be coated later if we decide that it is necessary.

Thank you.